

X-ray binaries and ultra-luminous X-ray sources in nearby and distant galaxies

Marat GILFANOV

Max-Planck-Institut für Astrophysik, Garching, Germany
Space Research Institute, Moscow, Russia

We review recent results on populations of compact X-ray sources in normal galaxies. The luminosity distributions of low and high mass X-ray binaries in nearby galaxies appear to be described by the respective “universal” luminosity functions, whose shapes do not vary significantly from galaxy to galaxy and the normalizations are proportional to the SFR (HMXBs) and stellar mass (LMXBs) of the host galaxy. There is a significant qualitative difference between XLFs of high and low mass X-ray binaries, reflecting the difference in the accretion regimes in these two types of X-ray binaries.

The high luminosity cut-off is by an order of magnitude larger for HMXBs – although bright sources, $\log(L_X) \geq 39$, are observed in both young and old galaxies, the truly ultra-luminous ones, with $\log(L_X) \sim 40 - 40.5$, are associated with the regions of intense star formation and have not been detected so far in old stellar populations of elliptical and S0 galaxies. The L_X –SFR relation for distant galaxies in the HDF-N indicates that ULXs at redshifts of $z \sim 0.2 - 1.3$ were not significantly more luminous than those observed in nearby galaxies.

§1. Introduction

Chandra observatory, thanks to its sub-arcsec angular resolution, opened a new era in studying X-ray binary populations in nearby galaxies. For the first time an opportunity was presented to observe compact sources in a nearly confusion free regime. The long suspected fact has been proved, that X-ray binaries are an important, if not dominant, contributor to the X-ray emission of the normal galaxies,⁴⁾ as illustrated by the example of our Galaxy.⁸⁾

Depending on the mass of the optical companion, X-ray binaries are subdivided in to two classes – low and high mass X-ray binaries, having significantly different evolutionary time scale, $\sim 10^{6-7}$ and $\sim 10^{9-10}$ years respectively.²²⁾ The nearly prompt emission of HMXBs makes them a potentially good tracer of the recent star formation activity in the host galaxy.²¹⁾ The LMXBs, on the other hand, have no relation to the present star formation, but, rather, are related to the stellar content of the host galaxy.⁶⁾ Chandra observations of the nearby galaxies presented a possibility to confirm this simple picture and to calibrate the HMXB–SFR^{5), 9), 19)} and LMXB– M_* ^{2), 6), 13)} relations.

An unusual class of compact sources – ultraluminous X-ray sources, has been discovered in nearby galaxies more than a decade ago.^{1), 3)} Although bright, $L_X > 10^{39}$ erg/s, point-like sources are found both in young star forming galaxies and in old stellar population of elliptical and S0 galaxies, the most luminous and exotic objects are associated with actively star forming galaxies. Their nature and relation to more ordinary X-ray binaries is still a matter of a significant debate. Based on a simple

Eddington luminosity argument, they appear to be powered by accretion onto an intermediate mass object – a black hole with the mass in the hundreds-thousands solar masses range.^{4),16)} However, a number of alternative models have been considered as well – from collimated radiation¹⁵⁾ to \sim stellar mass black holes, representing the high mass tail of the standard stellar evolution sequence and accreting in the near- or slightly super-Eddington regime.¹⁴⁾

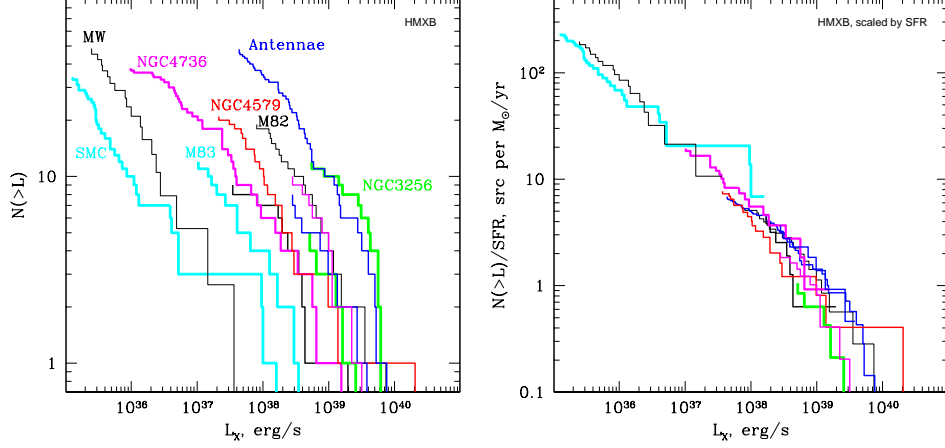


Fig. 1. *Left:* The XLFs of compact X-ray sources in nearby star forming galaxies. *Right:* The XLFs of the same galaxies normalized to the star formation rates (from Grimm et al.⁹⁾). The XLF of the Milky Way includes only HMXBs.

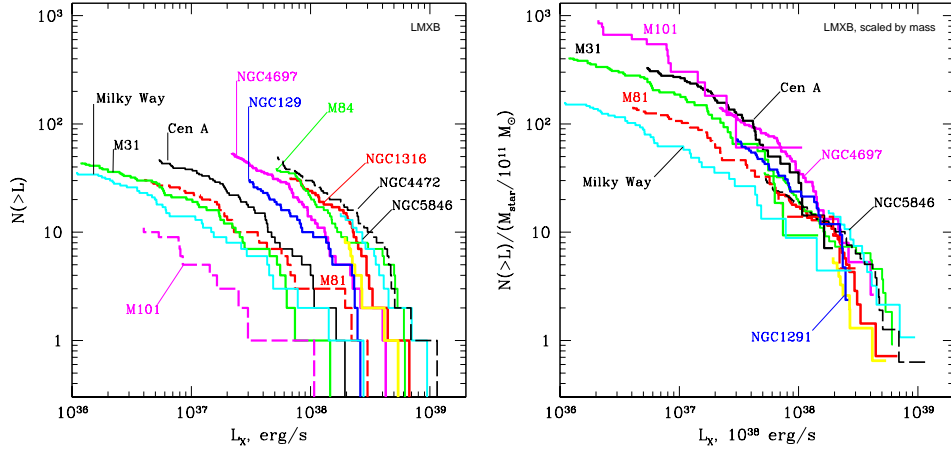


Fig. 2. *Left:* The XLFs of compact X-ray sources in nearby elliptical, S0 galaxies and bulges of spiral galaxies. *Right:* The same XLFs normalized to the stellar mass of the host galaxy (from Gilfanov⁶⁾). The XLF of the Milky Way includes only LMXBs.

§2. “Universal” XLFs of high- and low- mass X-ray binaries

The Fig.1 (left panel) shows observed luminosity functions (XLFs) of compact X-ray sources in nearby star forming galaxies from the sample of Grimm et al.⁸⁾ There is a large spread in the number of sources and in the luminosity of the brightest source among the galaxies. However, normalized to the SFR of the host galaxy, the XLFs match each other both in the slope and in the normalization (right panel in Fig.1). Although a finite dispersion might still remain, especially at the high luminosity end, the normalized luminosity functions occupy a rather narrow band in the $N - L_X$ plane, despite of the large dynamical range of the star formation rates, a factor of ~ 50 . Similarly, the XLFs of the compact sources in the old stellar systems – elliptical, S0 galaxies and bulges of spiral galaxies differ significantly from each other, but the

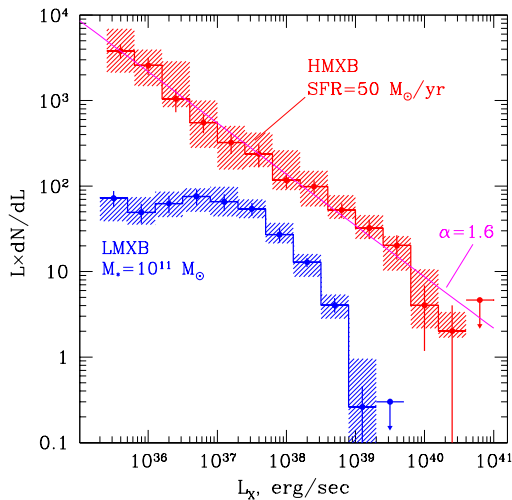


Fig. 3. The “universal” XLFs of high- and low-mass X-ray binaries in nearby galaxies (from Grimm et al.⁹⁾ and Gilfanov⁶⁾). The upper limits are at 90% confidence for a Poisson distribution. The shaded areas illustrate the amplitude of systematic errors (90% confidence level) due to uncertainties in the source distance (assuming 20% relative uncertainty), mass-to-light ratios (30%) and star formation rates (30%).

range it has the differential slope of $\approx 1.8 - 1.9$. This difference in the “universal” XLFs reflects the difference in the accretion regimes in low- and high-mass X-ray binaries. The majority of high mass systems are wind accretors and their \dot{M} distribution is governed by the properties of the optical companion, mainly by their luminosity/mass distribution.¹⁸⁾ The LMXBs, on the contrary, are close binaries fed via Roche lobe overflow and the \dot{M} in such systems is generally defined by the angular momentum loss rate, which, in turn, depends on the binary system parameters.

dispersion decreases notably after they are normalized to the stellar mass of the host galaxy (Fig.2). These examples suggest that the luminosity distributions of HMXBs and LMXBs are described, to first approximation, by the “universal” XLFs, whose shapes are not subject to significant galaxy-to-galaxy variations. Their normalizations are proportional, respectively, to the SFR and stellar mass of the host galaxy.^{6),9)}

The shapes of the universal XLFs of high- and low-mass X-ray binaries in nearby galaxies are qualitatively different from each other (Fig. 3). The HMXB XLF can be approximated by a power law with differential slope of $\alpha \approx 1.6$ in a broad luminosity range, $\log(L_X) \sim 35.5 - 40.5$ and has a cut-off at $\log(L_X) \sim 40.5$. The shape of the LMXB XLF is more complex. It appears to follow the L^{-1} power law at low luminosities, gradually steepens at $\log(L_X) \geq 37.0 - 37.5$ and has a rather abrupt cut-off at $\log(L_X) \sim 39.0 - 39.5$. In the $\log(L_X) \sim 37.5 - 38.7$ luminosity

2.1. Universal XLFs and binary evolution

Existence of “universal” XLFs is somewhat surprising. The shape of the luminosity function is defined by a number of factors, such as metallicity and star formation history of the host galaxy. The importance of the latter is illustrated by the example of low mass X-ray binaries. Indeed, a luminosity of 10^{38} erg/s requires a mass accretion rate of $\sim 10^{-8} M_{\odot}/\text{yr}$, which can be sustained by a low mass star for less than $\leq 10^8$ yrs.¹⁷⁾ This is significantly shorter than the life time of a galaxy. It is yet shorter for the most luminous LMXB systems with $L_X \sim 10^{39}$ erg/s. In order to have the presently observed shape of the LMXB XLF, with a moderate fraction of sources with $L_X \geq 10^{38}$ erg/s, in the stellar systems of the age of $\sim 10^{10}$ yrs, a continuous replenishment of the high luminosity sources is required. Such a replenishment can be maintained, for example, due to binary systems with initially less massive companion stars, reaching the X-ray active phase at later times. An evolution of the luminosity function with time passed after the star formation event must be present and it should be more pronounced at the high luminosity end of the XLF. However, the results of Grimm et al.⁹⁾ and Gilfanov⁶⁾ suggest that there are no significant galaxy-to-galaxy variations of the shape of the luminosity distributions of X-ray binaries in nearby galaxies. A possible explanation is that the nearby galaxies studied in Ref. 6), 9) have similar ages of the stellar populations, with the more subtle variations being masked by statistical errors. The latter limitation is unavoidable due to limited number of (bright) sources per galaxy.

§3. L_X –SFR and $L_X - M_*$ relations

The total numbers of LMXBs and HMXBs in a galaxy are proportional to its stellar mass and star formation rate respectively. The same is true for the combined X-ray luminosities of X-ray binaries in the limit of large SFR and stellar mass (Fig. 4). In the low SFR and stellar mass regime the L_X –SFR and $L_X - M_*$ relations are modified by the effects of small number statistics, as discussed below. The most pronounced these effects are for HMXBs.

3.1. Effects of small number statistics in the L_X –SFR and $L_X - M_*$ relations

An intuitively obvious expression for the total luminosity can be obtained integrating the luminosity distribution:

$$\langle L_{\text{tot}} \rangle = \int_{L_{\text{min}}}^{L_{\text{cut}}} \frac{dN}{dL} L dL \propto N_{\text{tot}} \propto \text{SFR or } M_* \quad (3.1)$$

implying, that the total luminosity is proportional to the number of sources, i.e. to the star formation rate or stellar mass. However, as discussed by Gilfanov et al.,⁷⁾ the quantity of interest is a sum of luminosities of discrete sources:

$$L_{\text{tot}} = \sum_k L_k \quad (3.2)$$

where L_k are distributed according to the luminosity function dN/dL . Depending on the properties of dN/dL , the probability distribution for the total luminosity,

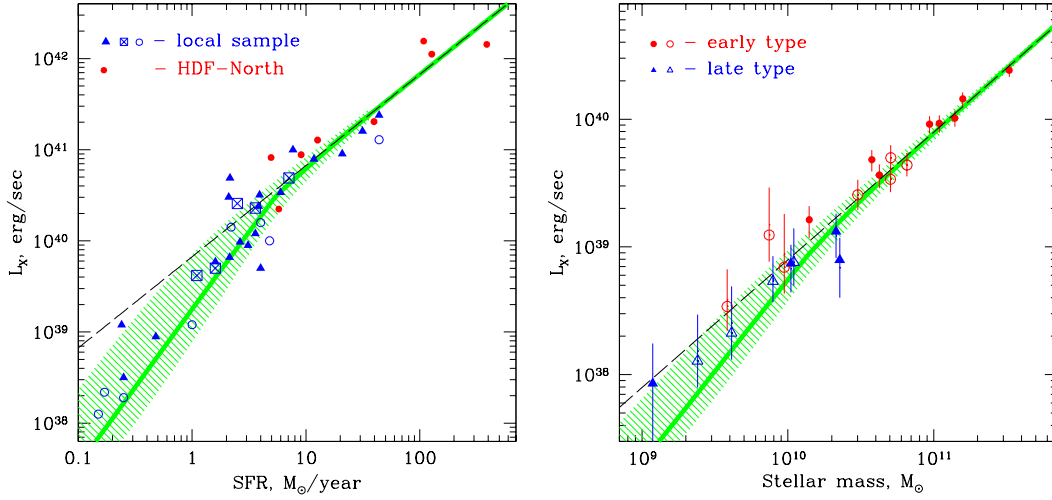


Fig. 4. The L_X –SFR (left) and L_X – M_* (right) relations for high- and low-mass X-ray binaries respectively. The thick grey lines and shaded areas show the relations for the most probable value of the total luminosity and its 67% intrinsic spread, predicted from the respective “universal” XLFs, the dashed lines show linear relations for the expectation mean. From Grimm et al.⁹⁾ and Gilfanov.⁶⁾

$p(L_{\text{tot}})$, can have a complex shape. Most importantly, it depends on the total number of sources and can be significantly asymmetric for small SFR or M_* , as illustrated by left panel in Fig. 5. Obviously, the luminosity of a randomly chosen galaxy will most likely be close to the value, at which $p(L_{\text{tot}})$ has the maximum (the mode of the probability distribution). Owing to the skewness of the $p(L_{\text{tot}})$ in the low-SFR and low- M_* regime, its mode does not equal the expectation mean defined by eq. 3.1. If observations of many galaxies with the same star formation rate (or stellar mass) are performed, the measured values of L_{tot} will be distributed according to $p(L_{\text{tot}})$. Their average will be always equal to the expectation mean, shown by the dashed straight line in the left panel of Fig.5. Of course, in the limit of $N_{\text{tot}} \rightarrow \infty$ the $p(L_{\text{tot}})$ asymptotically approaches the normal distribution, in accord with the Central Limit Theorem.

The difference between the mode and expectation mean is further illustrated by Fig.4, showing the predicted L_X –SFR and L_X – M_* relations along with the data of Chandra observations of nearby and (for HMXBs) distant galaxies in HDF-N. The thick solid lines in the figure show the SFR and M_* dependence of the mode of the $p(L_{\text{tot}})$ and predict the *most probable* value of the X-ray luminosity of a *randomly chosen* galaxy. The dashed lines show the expectation mean – the average luminosity of a large number of galaxies with the same SFR or M_* , which depend linearly on the SFR and M_* . For the shape of the LMXB XLF, the total luminosity of LMXBs is defined by the sources with luminosity $\log(L_X) \sim 37 - 37.5$. Correspondingly, the effects of small number statistics, although present in the L_X – M_* relation, are less important than in the L_X –SFR relation (Fig. 4).

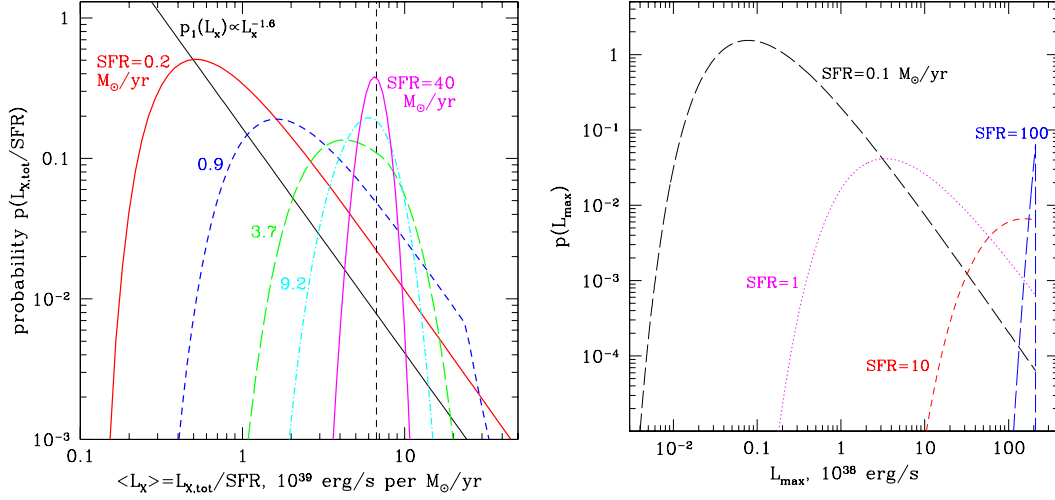


Fig. 5. The probability distributions of the total luminosity of HMXBs (*Left*) and of the luminosity of the brightest HMXB in a galaxy (*Right*) for different values of SFR. The vertical dashed line in the left panel shows the expectation mean. Both distributions are computed using the parameters of the “universal” luminosity function of HMXBs. From Gilfanov et al.⁷⁾

Validity of the L_X –SFR relation beyond the local Universe was confirmed by the Chandra observations of star forming galaxies at $z \approx 0.2 - 1.3$ in HDF-N. The $L_X - M_*$ relation for LMXBs was studied for local galaxies only, within $\sim 20 - 30$ Mpc from the Sun. Due to binary evolution effects, this relation can be different for younger galaxies, located at intermediate redshifts.

§4. Luminosity of the brightest source in a galaxy

As the first Chandra observations of compact sources in nearby galaxies became available, it has been noted^{(4), (10), (20)} that the luminosity of the brightest X-ray binary in a galaxy might depend on its properties. It appeared to correlate with the star formation rate (HMXBs) and stellar mass (LMXBs) of the host galaxy. For example, in the Antennae galaxies, a number of compact sources have been discovered with luminosities of $\sim 10^{40}$ erg/s.⁽²³⁾ On the other hand, the luminosities of the brightest HMXB sources in the Milky Way do not exceed $\leq 10^{38}$ erg/s.⁽⁸⁾ It has been argued that this might reflect the difference in the intrinsic source properties, related to the SFR-dependent difference in the galactic environment and in initial conditions for X-ray binary formation.

However, as was noted in Ref. 6), the probability distribution for the luminosity of the brightest source in a galaxy, $p(L_{max})$, depends non-trivially on the LF normalization, i.e. on the SFR or the stellar mass of the host galaxy (right panel in Fig. 5). This leads to the dependence of the most probable value of the luminosity of the brightest source on, for example, the star formation rate of the galaxy – L_{max} increases with SFR, until it reaches the maximum possible value, defined by the high

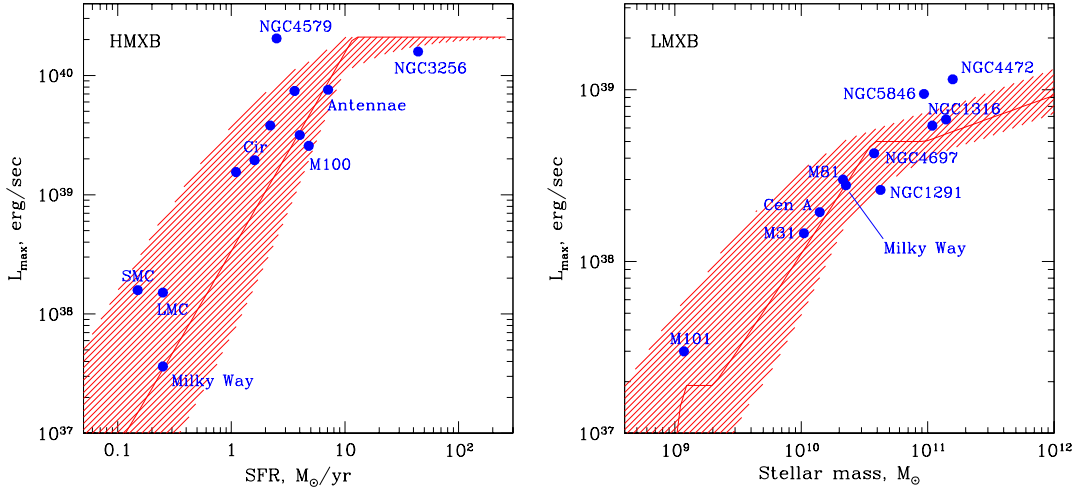


Fig. 6. *Left*: The luminosity of the brightest HMXB (*left*) and LMXB (*right*) in a galaxy as a function of the star formation rate and the stellar mass respectively. The solid lines and the shaded areas show the most probable value of the L_{\max} and its 67% intrinsic dispersion, calculated from the respective “universal” XLFs. The filled circles show L_{\max} observed in the nearby galaxies and in the Milky Way. The “broken” shape of the predicted dependence in the right panel is a consequence of the broken power law approximation of the “universal” LMXB XLF, used in the calculations. From Gilfanov.⁷⁾

luminosity cut-off of the LF, as illustrated by Fig. 6. Filled symbols in Fig. 6 show the luminosities of the brightest source observed with Chandra in nearby galaxies. The large difference in the maximum luminosity between low- and high-SFR galaxies, e.g. between the Milky Way and the Antennae galaxies, or between massive elliptical galaxies and the bulges of spiral galaxies can be naturally understood in terms of the properties of the probability distribution $p(L_{\max})$. So far there is no evidence for the significant dependence of intrinsic properties of X-ray binaries on the galactic environment.

§5. Variability of the total emission of X-ray binaries

X-ray flux from X-ray binaries is known to be variable in a broad range of time scales, from \sim msec to \sim years. In addition to a number of coherent phenomena and quasi-periodic oscillations, significant continuum aperiodic variability is often observed. The fractional rms of aperiodic variations depends on the nature of the binary system and the spectral state of the X-ray source and is usually in the range from a fraction of a per cent to $\sim 20 - 30$ per cent.

As flux variations of the individual sources are uncorrelated, one might expect that the fractional *rms* of the total emission should decrease with the number of sources n as $rms \propto 1/\sqrt{n} \propto 1/\sqrt{L_{\text{tot}}}$. Although correct in the limit of large n , this intuitively obvious prediction can break down for small number of sources. Indeed, for a sufficiently flat luminosity function, a regime exists, when the total luminosity is

defined by a few brightest sources. To first approximation the number of such sources does not depend on the total number of sources. Consequently, in this regime the fractional rms of the total emission depends weakly or does not depend at all on the total number of sources or on their total luminosity (i.e. on SFR or M_*). This behavior is illustrated by the results of the Monte-Carlo simulations, shown in Fig.7 as $rms - L_{\text{tot}}$ relations for HMXBs and LMXBs.

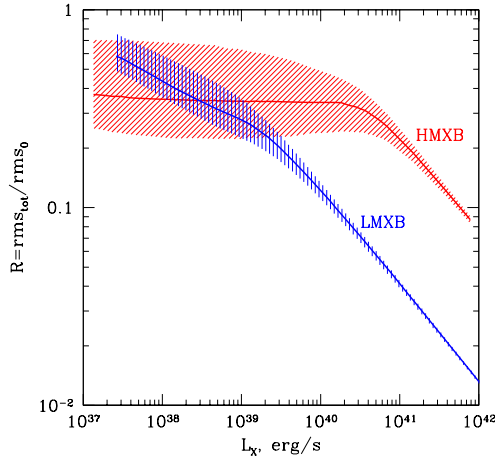


Fig. 7. Fractional rms of combined emission of HMXBs and LMXBs as a function of their total luminosity. The rms_0 denotes rms of one source, assumed to be the same for all sources. The thick solid lines and shaded areas show the most probable value of the rms/rms_0 , and its 67% confidence interval, both obtained from the Monte-Carlo simulations for the respective “universal” XLFs. At high L_X both curves follow $rms \propto 1/\sqrt{L_X}$ averaging law.

ified by the luminosity dependence of the rms of individual sources. This factor might become especially important for HMXBs at large values of SFR when the total luminosity of a star forming galaxy is dominated by ULXs whose variability properties we know little about.

§6. X-ray binaries, ULXs and intermediate mass black holes

The cut-off luminosity in the LMXB XLF is by a factor of ~ 10 smaller than in HMXB XLF (Fig. 3) and does not exceed $\log(L_X) \sim 39.5$. Earlier report of detection of the sources with luminosity significantly greater than $\sim 10^{39}$ erg/s in early type galaxies are most likely related to miss-identifications of the CXB sources, erroneously attributed to the galactic source populations.^{6),11)} Quantitatively, the value of the high luminosity cut-off in the LMXB XLF, $\log(L_X) \sim 39 - 39.5$ does

For moderate star formation rates, $SFR \leq 5 - 10 M_\odot/\text{yr}$, we predict a rather large aperiodic variability of the total emission of HMXBs at the level of $\sim 1/3 - 1/2$ of the fractional rms of individual X-ray binaries. At larger values of SFR, corresponding to the linear regime in the $L_X - SFR$ relation, it decreases as $rms \propto 1/\sqrt{SFR} \propto 1/\sqrt{L_{\text{tot}}}$, in accord with the averaging law. For LMXBs, owing to the shape of their “universal” XLF, the fractional rms of the total emission decrease rather quickly with M_* and L_{tot} in the entire mass range of interest. Consequently, considerable variability on the level of $\sim 1/4 - 1/2$ of that of individual X-ray binaries can be expected only for light bulges of spiral galaxies with masses in the $\log(M_*) \sim 9.5 - 10.5$ range. In the bright luminosity end, $\log(L_X) \geq 39.5$, the X-ray emission from early type galaxies is expected to be significantly, up to a factor of ~ 7 , less variable than from star forming galaxies. The predicted $rms - L_X$ relations can be mod-

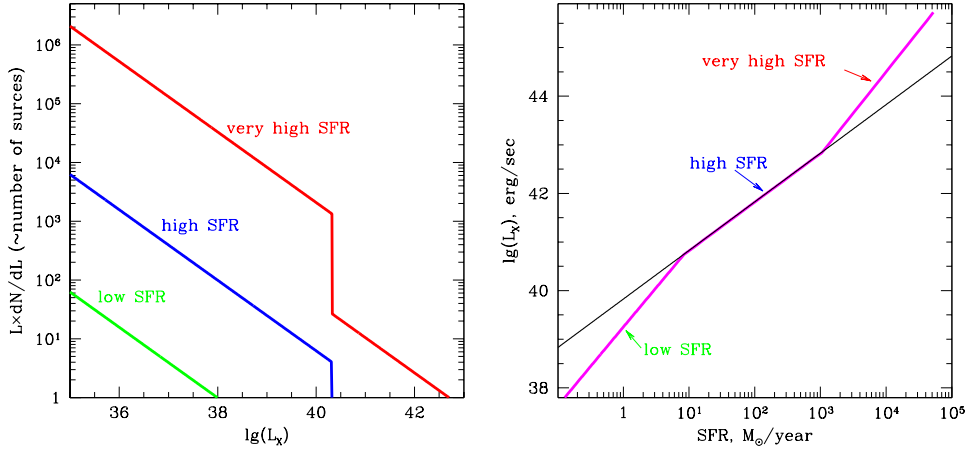


Fig. 8. Illustration of the effect of hypothetical intermediate mass black holes on the L_X –SFR relation. *Left*: The luminosity function of compact sources at different levels of star formation rate. *Right*: Corresponding L_X –SFR relation. The thin straight line shows the linear dependence.

not present a problem from the point of view of the Eddington luminosity limit for a stellar mass object and can be easily explained by a sub- or near-critical accretion onto a ~ 10 – $15 M_\odot$ black hole – there are no “real” ULXs in old stellar systems. The truly exotic are the objects associated with the regions of intensive star formation, having luminosities above $\sim 10^{40}$ erg/s.

Surprising is the smooth, single slope power law shape of the “universal” luminosity function of X-ray sources in star forming galaxies, without any significant steps and features in a broad luminosity range, $\lg(L_X) \sim 36 - 40.5$ (Fig.3). The high luminosity end, $\lg(L_X) > 39$, of this distribution corresponds to ultraluminous X-ray sources. Its low luminosity end, on the other hand, is composed of ordinary X-ray binaries, powered by accretion onto a \sim stellar mass compact objects. This result constrains the range of possible models for ULXs. Their frequency and luminosity distributions should be a smooth extension toward higher luminosities of that of “ordinary” \sim stellar mass systems, emerging from the standard stellar evolution sequence. Although some of the ULXs might be indeed rare and exotic objects, it appears that majority of them cannot be a completely different type of the source population, but, rather, represent the high mass, high \dot{M} tail of the “ordinary” HMXB population.

The position of the break between the non-linear and linear parts of the L_X –SFR relation depends on the LF slope and its cut-off luminosity: $\text{SFR}_{\text{break}} \propto L_{\text{cut}}^{\alpha-1}$. This allows one to constrain the parameters of the luminosity distribution of compact sources using the data of spatially unresolved galaxies. Agreement of the predicted L_X –SFR relation with the data both in high- and low-SFR regimes confirms the universality of the HMXB luminosity function, derived by Grimm et al.⁹⁾ from significantly fewer galaxies (shown as crossed boxes) than plotted in Fig.4. It provides an independent confirmation of the existence of a cut-off in the HMXB XLF at

$\log(L_{\text{cut}}) \sim 40.5$, thus confirming that the luminosity of ULXs in the nearby galaxies has a maximum value of the order of $\lg(L_X) \sim 40.5$. The fact that the (spatially unresolved) galaxies from the Hubble Deep Field North obey the same L_X –SFR relation (Fig.4), implies, that the ULXs at the redshift of $z \sim 0.2 - 1.3$ were not significantly more luminous, than those observed in the nearby galaxies.

The hypothetical intermediate mass black holes, probably reaching masses of $\sim 10^{2-5} M_\odot$, might be produced, e.g. via black hole merges in dense stellar clusters, and can be associated with extremely high star formation rates. To accrete efficiently they should form close binary systems with normal stars or be located in dense molecular clouds. It is natural to expect, that such objects are significantly less frequent than \sim stellar mass black holes. The transition from \sim stellar mass BH HMXB to intermediate mass BHs should manifest itself as a step in the luminosity distribution of compact sources (Fig.8, left panel). If the cut-off in the HMXB XLF, observed at $\log(L_{\text{cut}}) \sim 40.5$ corresponds to the maximum possible luminosity of “ordinary” \sim stellar mass black holes and if at $L > L_{\text{cut}}$ a population of hypothetical intermediate mass BHs emerges, it should lead to a drastic change in the slope of the L_X –SFR relation at extreme values of SFR (Fig.8, right panel). Therefore, observations of L_X –SFR relation for distant star forming galaxies with very high SFR might be a way to probe the population of intermediate mass black holes.

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